Energy, Mines and Resources Canada
Énergie, Mines et Ressources Canada

CANMET

Canada Centre for Mineral and Energy Technology
Centre canadien de la technologie des minéraux et de l'énergie

Mining Research Laboratories
Laboratoires de recherche minière

TENSILE STRENGTH TESTS ON URL ROCK SAMPLES FROM BOREHOLE 401-009-HF1

B. Gorski, and Y. S. Yu

MRL 91-080(TR) June 1991

Canada

92-01190/

TENSILE STRENGTH TESTS ON URL ROCK SAMPLES FROM BOREHOLE 401-009-HF1

B. Gorski, and Y. S. Yu

MRL 91-080(TR) June 1991

This document was produced by scanning the original publication.

Ce document est le produit d'une numérisation par balayage de la publication originale.

25 pp

MICROMEDIA

TENSILE STRENGTH TESTS ON URL ROCK SAMPLES FROM BOREHOLE 401-009-HF1

by

B. Gorski*, and Y. S. Yu**

ABSTRACT

Many devices have been developed over the years for the determination of the tensile strength of rock materials. The devices use both direct and indirect methods in the testing and subsequent determination of rock tensile strength. Of these, the direct pull tensile test is the preferred method. However, complications arise where laboratories are equipped with compression testing machines as opposed to tension testing machines. To overcome the problem, this laboratory has developed a direct tensile apparatus that may be fitted into any compression press or compression press triaxial chamber of suitable internal diameter. The tensile apparatus is unique in that as an axial compressive load is applied to the apparatus, tension in the axial direction is transmitted to the contained rock specimen.

The results of tensile strength tests conducted on grey granite using three different tensile test methods are also presented. The granite originates from AECL's Underground Research Laboratory, located in Pinawa, Manitoba. The tensile strength of grey granite from the 420 level was found to be considerably lower than values for the 240 level.

---

*Physical Scientist,**Research Scientist, Canadian Mine Technology Laboratory
Mining Research Laboratories, CANMET, Energy, Mines and Resources Canada, Ottawa, Canada

Keywords:

Brazilian test, triaxial extension test, direct tensile strength test, finite element.

ESSAIS DE RÉSISTANCE À LA TRACTION MENÉS SUR DES CAROTTES D'ÉCHANTILLONS DU LRS TIRÉES DU TROU DE SONDE 401-009-HF1

par

B. Gorski* et Y.S. Yu**

RÉSUMÉ

Au fil des années, on a mis au point de nombreux appareils servant à déterminer la résistance à la traction des matériaux rocheux. Ces appareils font appel à des méthodes d'essai de traction directes et indirectes pour faire l'essai d'échantillons de roches et en déterminer la résistance à la traction. De toutes ces méthodes, on préfère celle dite d'essai de traction directe. Toutefois, des complications se posent dans les laboratoires qui sont équipés de machines d'essais à la compression plutôt que de machines d'essai à la traction. Afin de surmonter le problème, le Laboratoire canadien de technologie minière a mis au point un appareil d'essai de traction directe qui peut être monté sur n'importe quelle presse de compression ou chambre triaxiale de presse de compression, dont le diamètre interne est suffisant pour les besoins. Le caractère unique de l'appareil tient au fait qu'on lui applique une charge axiale en compression et que la tension en direction axiale est transmise à l'échantillon qui s'y trouve.

Le rapport présente aussi les résultats d'essais de résistance à la traction menés sur du granite gris à l'aide de trois méthodes différentes. Les granites proviennent du Laboratoire de recherche souterrain de l'EACL, à Pinawa, au Manitoba. On a constaté que la résistance à la traction du granite gris du niveau 420 est beaucoup moins élevée que celle du granite provenant du niveau 240.

---

*Spécialiste des sciences physiques, **chercheur scientifique, Laboratoire canadien de technologie minière, Laboratoires de recherche minière, CANMET, Énergie, Mines et Ressources Canada, Ottawa, Canada

Mots clés :

Essai brésilien, essai de traction triaxiale, essai de résistance à la traction directe, élément fini.

TABLE OF CONTENTS

		Page
	ABSTRACT	i
	RÉSUMÉ	ii
1.0	INTRODUCTION	1
2.0	BACKGROUND: TENSILE TESTING	1
3.0	APPARATUS DESIGN	3
4.0	SPECIMEN PREPARATION	4
5.0	BRAZILIAN TEST	5
6.0	TRIAXIAL EXTENSION TEST	6
7.0	NEW DIRECT TENSILE TEST	7
8.0	TEST RESULTS	7
9.0	NUMERICAL MODELLING OF TENSILE SPECIMENS	8
	Finite Element Stress Analysis:	8
	Finite Element Models:	8
	Model No. 1:	8
	Model No. 2:	11
	Model No. 3:	11
	Model No. 4:	11
	Material Properties	11
	Tractions	11
10.0	TENSILE NUMERICAL MODELLING RESULTS	12
11.0	TENSILE STRENGTH RESULTS	13
12.0	OBSERVATIONS	13
13.0	DISCUSSION AND CONCLUSIONS	14
14.0	RECOMMENDATIONS	14
15.0	REFERENCES	16

FIGURES

No.

Fig. 1 Detail of new direct tensile apparatus 2
Fig. 2 Specimen geometry 3
Fig. 3 Specimen grinding set-up 5
Fig. 4 Triaxial extension test set-up 6
Fig. 5 Axisymmetric solid subjected to arbritrary loads 9
Fig. 6 A schematic diagram showing only a quarter of the specimen 10
Fig. 7 Stress along the center section of the specimen (sectio AB or A'B') . . . 19
Fig. 7 Stress along the 'neck' section of the specimen (section D'D or C"C) . . 20

TABLES

No.

1 Specimen Test Data 17
2 A Description of the Numerical Models 18

1. INTRODUCTION

Atomic Energy of Canada Limited (AECL) is conducting geomechanical research at its Underground Research Laboratory (URL) in southeastern Manitoba. The purpose of the research program is to assess the feasibility of nuclear fuel waste disposal deep in a plutonic rock mass.

Three series of tensile strength tests have been carried out on URL vertical rock core samples from borehole 401-009-HF1 located at 420 m level. This report presents these results, determined by three different test methods.

2. BACKGROUND: TENSILE TESTING

The tensile strength of rock specimens has been investigated by many researchers in the field of rock mechanics using different test configurations. As rock is much weaker in tension than in compression, the need for reliable tensile tests requires special attention. Various methods for tensile strength of rocks, such as the direct methods with special collars, grips, fixtures, involving the use of different bonding media at the gripping ends of the sample, have come into practice. A review of other methods such as: bending tests, ring tests, disc tests and other methods have been presented by Vutukuri et al. [1]. Because, the validity of tensile strength values is dependent on the application of a uniform stress distribution during the test, Vutukuri has expressed doubt in the reliability of results derived using these indirect methods.

Of the known indirect methods, the Brazilian tensile test is the most commonly used, due to the ease of sample preparation and set-up. The direct-pull method is considered to be the best for any effective evaluation of the tensile strength of rock. However, the application of direct methods to rocks introduces difficulties in gripping the specimen without damaging the surface and in applying a tensile load parallel to the axis of the specimen without bending the sample and consequently causing abnormal stress concentration at the grip ends.

The Mining Research Laboratories has developed a simple tensile apparatus to perform tensile strength tests on rock specimens (Fig. 1). The apparatus is unique in that it is designed to fit in a compression press having no tension capabilities. The compression of the apparatus in the press transmits direct tension in the rock specimen. The apparatus can be installed in a triaxial chamber. Also by suitably jacketting the specimen, the method can be used under elevated temperature conditions.

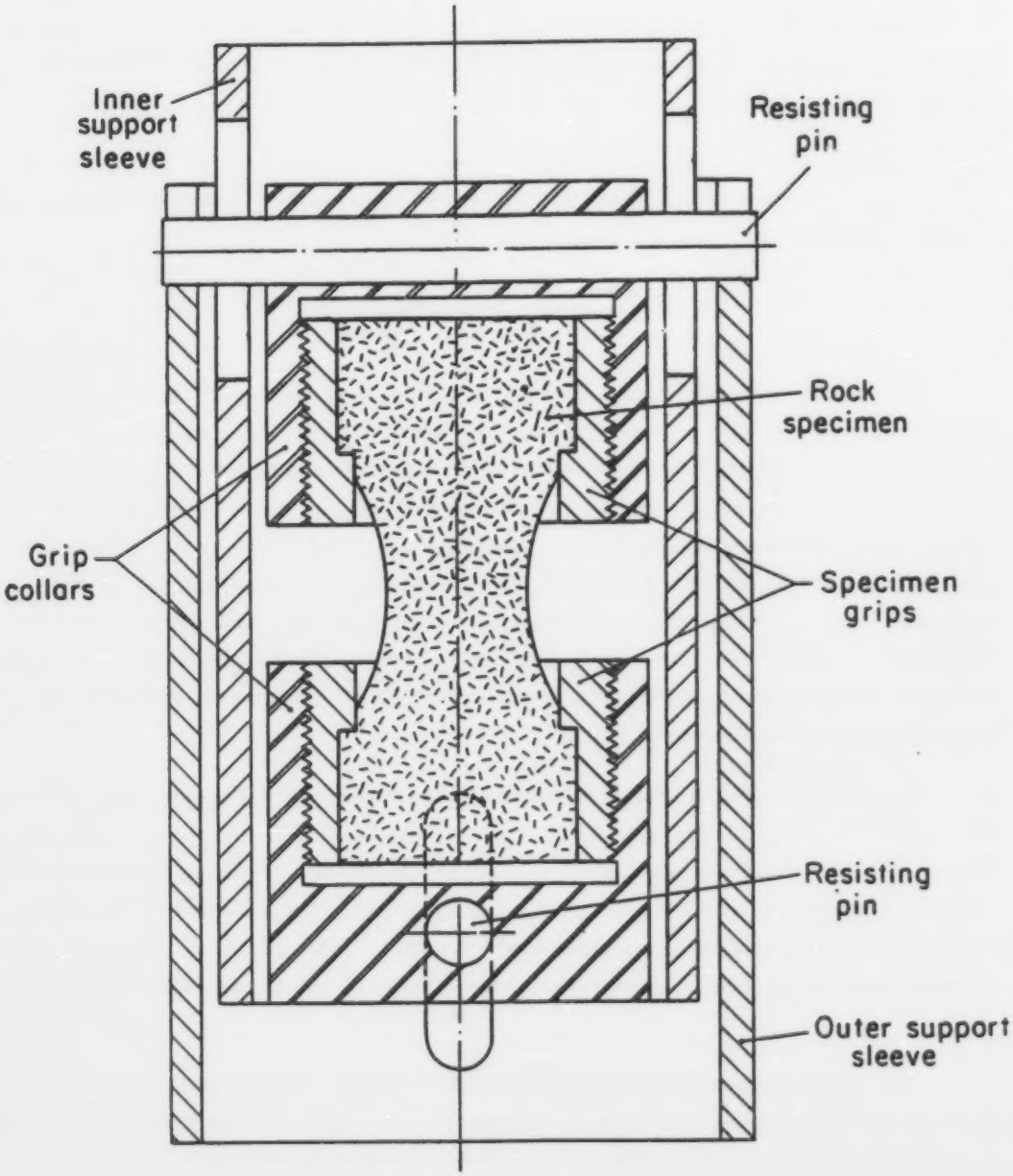


Fig. 1 Detail of new direct tensile apparatus

3. APPARATUS DESIGN

The test apparatus is suited to 45 mm diameter rock specimens having lengths of approximately 100 mm. However, the apparatus may be made to suit any required specimen size. Figure 1 illustrates the design details of the split grip tensile apparatus in cross section. All the machined parts are made of mild steel. In order to ensure perfection in the alignment of the specimen to the loading axis, the grips are split then machined and threaded as a single piece. The split grips hold the specimen near it's ends.

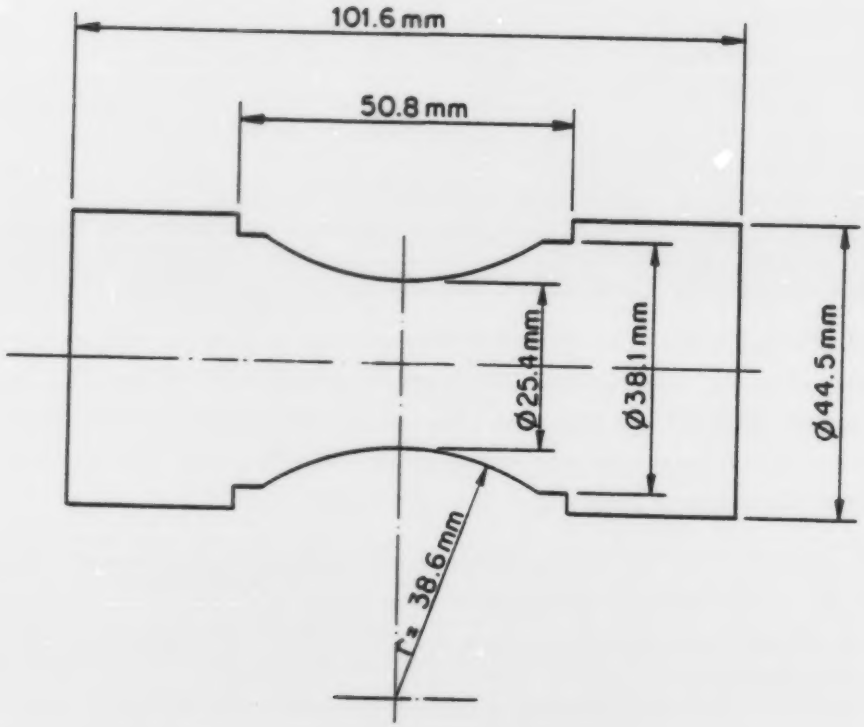


Fig. 2 Specimen geometry

The split grip sets are shouldered with internal diameters of 44.45 mm and 38.10 mm. This shoulder mates the shoulder of the rock specimen thereby allowing the rock to be pulled apart (Fig. 2).

The split grip pairs, placed on the cylindrical ends of the rock specimen are threaded, as a unit, into the grip collars. Once the grip collars are threaded on, a cylindrical sleeve, having two holes at the top, is installed over the assembled rock specimen.

A hole through the bottom grip collar is aligned with two matching holes of the sleeve and then a resisting steel pin is slid into place. A hole through the top grip collar is aligned 90° to the bottom grip collar hole. A resisting steel pin is then slid through the two slotted holes drilled through the upper part of the steel sleeve and through the top grip collar hole. The assembled sample together with the sleeve are then installed in a larger diameter sleeve and suspended on it by the upper pin bearing on two half slotted holes located at the top of the outer sleeve. The apparatus is self-aligning under load.

4. SPECIMEN PREPARATION

The test specimens were cut from the received core. Ten Brazilian test specimens were prepared. Ten direct tensile specimens were contoured using a machinist's lathe equipped with a tool post grinder (Fig. 3). The grinder was equipped with a diamond impregnated grinding wheel. The specimens were shouldered to accommodate the grip restraining seats (Fig. 2). The thickness of the grinding wheel was 10 mm. This provided a central uniform diameter, 10 mm long. The middle least diameter ensured failure at the mid-section. Ten triaxial extension test specimens were prepared using the machinist's lathe. These specimens were prepared without shoulders.

Rock core specimens selected for direct tensile tests were prepared with lengths 102 mm. Brazilian tensile strength specimens were prepared with length to diameter ratios of 1:2. All specimens were lapped to within specified ISRM [2] tolerances, room dried, weighed and dimensioned.

The depth, test type and density of each tested grey granite specimen, are listed in Table 1.

Fig. 3 Specimen grinding set-up

5. BRAZILIAN TEST

The test measures the uniaxial tensile strength of rock specimens indirectly. The test is based on the experimental fact that most rocks in biaxial stress fields fail in tension at their tensile strength when one principal stress is tensile and the other finite principal stress is compressive with a magnitude not exceeding three times that of the tensile principal stress. The test specimens were loaded to failure at diametrically opposed surfaces using a 2000 kN ELE compression press equipped with an 80 kN load cell. The test procedure conformed to ISRM standards [2].

6. TRIAXIAL EXTENSION TEST

Ten specimens were tested using a 'BX' Hoek cell and an MTS compression press. The test method was developed by Brace [5]. Figure 4 shows the test set up. Modelling clay was used as the medium to transmit side pressure from the straight sided urethane jacket to the curved surfaces of the specimen.

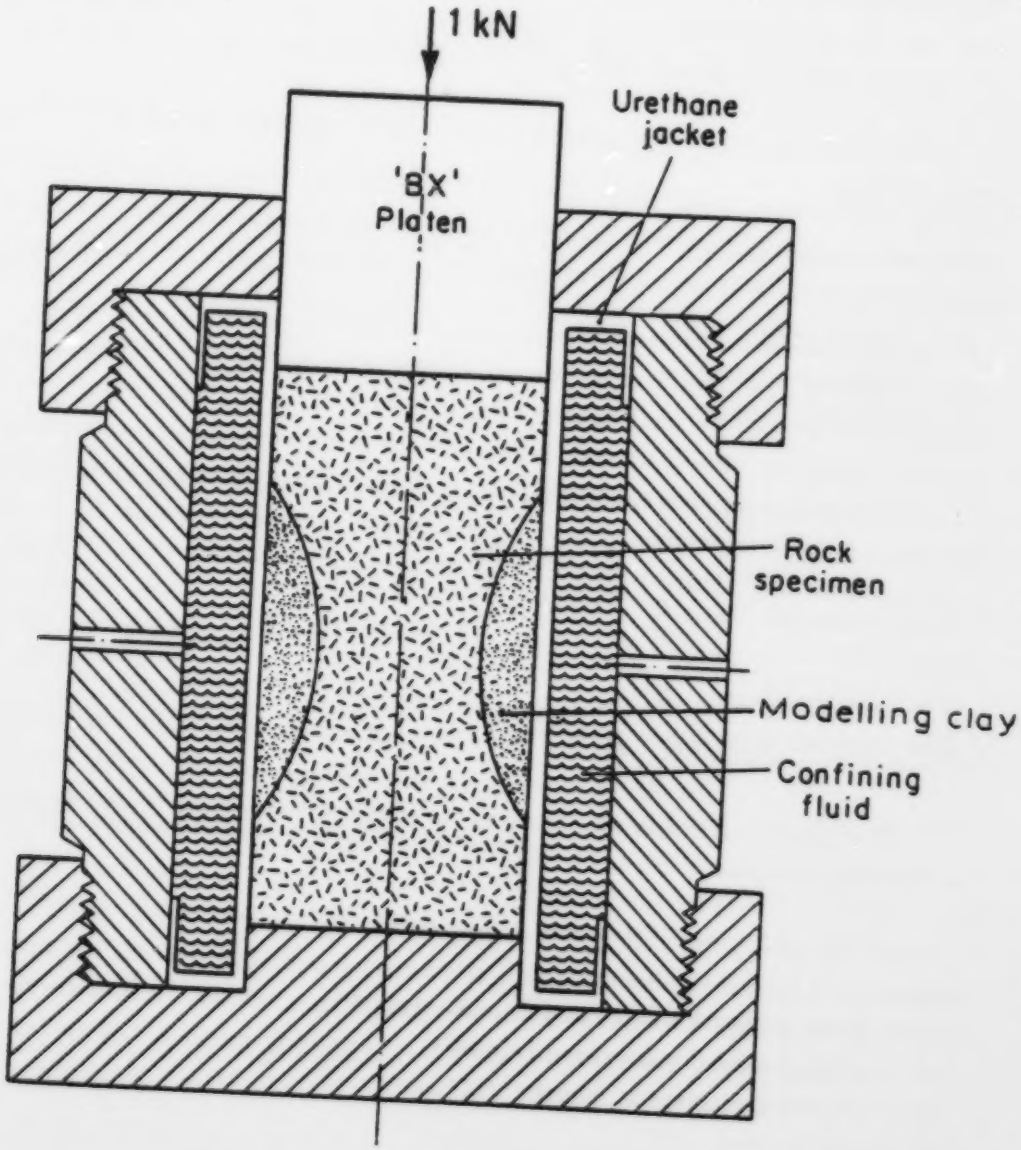


Fig. 4 Triaxial extension test set-up

7. NEW DIRECT TENSILE TEST

Ten specimens were tested using the new apparatus and an ELE 2000 kN compression press. The specimen was loaded in pressure control until specimen failure occured. Specimen load was monitored using an 80 kN load transducer. The stress rate applied to the specimen conformed ISRM prescribed standards.

8. TEST RESULTS

The Brazilian tensile strengths of the test specimens were calculated using the following formula.

Brazilian tensile strength $\sigma_t = \frac{2P}{\pi Dt}$ (MPa)

where

P = Load at failure (N)

D = Diameter (mm)

t = Thickness (mm)

The direct tensile strengths of the test specimens were calculated using the following formula.

Tensile strength $\sigma_t = \frac{P}{A}$ (MPa)

where

P = Load at failure (N)

A = Cross-sectional failure area (mm^2)

The triaxial extension tensile strengths of the test specimens were calculated using the following formula.

Tensile strength $\sigma_t = \frac{\sigma_3(A_1 - A_2)}{A_2} - \frac{P}{A_2}$ (MPa)

where

A_1 = Cross-sectional area at sample end (mm^2)

A_2 = Cross-sectional failure area (mm^2)

σ_3 = Confining pressure at failure (MPa)

P = Axial preload (N)

The tensile strength values are contained in Table 1.

9. NUMERICAL MODELLING OF TENSILE SPECIMENS

The tensile strengths derived from the direct tensile tests are considerably lower as compared to the Brazilian results of the same rock type. For the grey granite, the breakage occurred at or near the mid-section of the specimen.

To examine the failure mechanism of the direct tensile specimen, a numerical modelling program was set up to provide information on the stress distribution in the specimen. Data obtained from tensile tests performed on pink granite were used for this analysis [7].

Finite Element Stress Analysis:

Two software packages, SAP2D and NAOS, which are based on the finite element formulation were used for the analyses [8, 9]. SAP2D handles axisymmetric loading while NAOS is capable of handling axisymmetric geometry subjected to arbitrary loading.

A series of models were constructed to analyse the stress distribution within the specimen. The definition of axes and stresses are shown in Figure 5. For direct tensile tests, $P_x = P_y = 0$, and the appropriate tractions were applied on the load-bearing area of the shoulder to simulate the equivalent axial pull at failure. Due to symmetry, only one quarter of the core specimen needs to be simulated. Figure 6 shows a schematic diagram of the specimens in two dimensions. The analyses were first carried out using the software NAOS. To validate the accuracy of the analysis, SAP2D was also used. Both models yielded the same results.

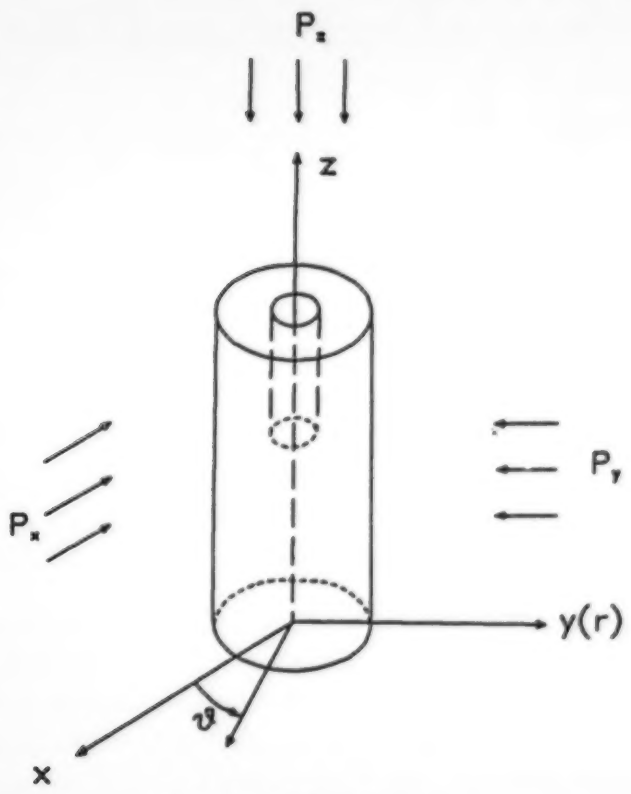
Finite Element Models:

Four models were constructed and used for the analyses. The detailed description of the models are given in Table 2 which is corresponding to Figure 6.

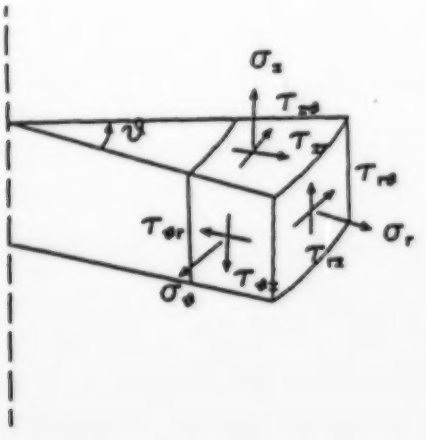
The four models are briefly described below:

Model No. 1:

This model simulates the original geometry and the loading conditions of the proposed tensile specimen. The tractions are applied on the whole load-bearing of the shoulders, i.e. the ring DE as shown in Figure 6. The load-bearing area is calculated by:

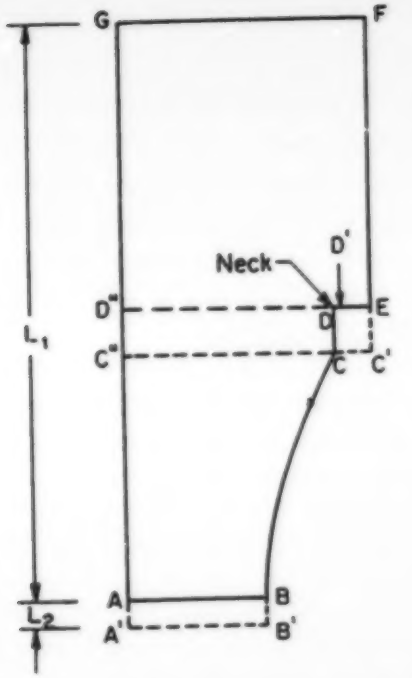


(a) Definition of axes

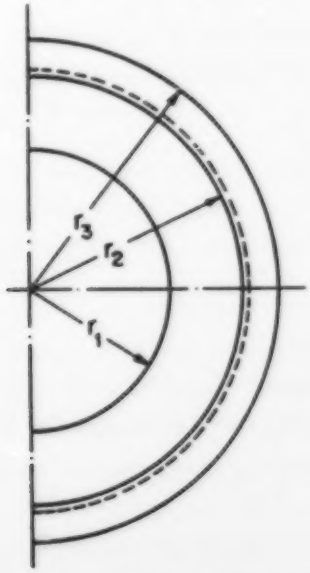


(b) Stresses acting on an infinites imal element within the stresses body

Fig. 5 Axisymmetric solid subjected to arbritrary loads



(a) Sectional view of the tensile specimen



(b) Plan view showing the area where the tractions were applied

Fig. 6 A schematic diagram showing only a quarter of the specimen

$A_{lb} = \pi$ x $(r_3^2 - r_2^2)$

where

$r_3 = 2.2225cm$

$r_2 = 1.9050cm$

Model No. 2:

The geometry of this model is identical to Model 1, however, the tractions are applied only on a 'partial' load-bearing area, i.e. the ring D'E as shown in Figure 6. In other words, the load-bearing area is calculated by:

$A_{lb} = \pi$ x $[r_3^2 - (r_2')^2]$

where

$(r_2') = r_2 + 1/32(in) = r_2 + 0.079375(cm)$

Model No. 3:

The central section of the specimen was extended to provide a uniform cross-section, while the tractions are applied on the whole load-bearing area, ring DE.

Model No. 4:

The sharp shoulder, DE, as shown in Figure 6, of the specimen was eliminated. The tractions are applied on the whole load-bearing area, as described in Model No. 1, and in Table 2.

Material Properties

The material properties of the pink granite required for the simulation are:

Young's Modulus E = 75 GPa

Poisson's ratio = 0.31

Density $\gamma = 2.62$ Mg/m^3

For the simulation of the tensile specimen the density was set to zero.

Tractions

The tractions, t, were calculated based on the pull load at failure, P, and the load-bearing area, A_{lb}.

The load-bearing area: $A_{lb} = \pi(r_3^2 - r_2^2)$ *or* $A_{lb} = \pi(r_3^2 - r'^2_2)$

The pull load at failure: $P = 2.66\ kN$

The traction: $t = A_{lb}/P = 6.641\ MPa$ *or* $8.45215\ MPa$

10. TENSILE NUMERICAL MODELLING RESULTS

The stress distribution along the center section (AB or A'B') and the 'neck' section (D"D or C"C) of the tensile specimen are shown, respectively, in Figures 7 and 8. These tensile stresses are acting in the axial (z) direction. The stresses for the plane with different angle θ are the same because of the axisymmetrical nature of the loading.

As expected, there is a high stress concentration around the 'neck' of the specimen. For Model No. 1, the tensile stress near the 'neck' and along the section D"D is 9.6 MPa; it is 1.78 times higher than the theoretical tensile stress of 5.25 MPa, at the center section. The tensile stresses along the center section of the rock specimen are not uniform and vary from 4.73 MPa at the center to 6.13 MPa near the 'skin' of the specimen.

To reduce the high stresses around the neck of the specimen, the tractions were applied on a reduced area leaving a gap of approximately 1/32th of an inch or 0.079375 cm between the collar of the specimen and the loading grip. As shown in Figures 7 and 8, the stresses reduced very slightly for both sections (Model No. 2).

To reduce the stress variation across the center section of the specimen, a uniform section was added to the model (Model No. 3). This model provided fairly uniform stress distribution at the center section, but they are generally larger than the theoretical value of 5.25 MPa. The stresses around the neck area are still much higher as compared with stresses along the center section, as shown in Figures 7 and 8.

For all the three models examined above, it is expected the break would occur around the neck area instead of the center section. When the tensile stress exceeds the tensile strength of the rock sample failure will be initiated at that point and propagated through the whole section around the neck.

However, for the pink granite, the majority of the specimens did break through the 'center' section [7]. It is postulated that the micro- structure of the specimen along the central portion of the tensile specimen could be affected by the excessive grinding leading to a strength reduction. However, the grinding process used included continuous flushing with cold water thereby dissipating any heat imparted by the blade to the rock specimen. The large grain size of the rock specimens may contribute to lower strengths as the grains themselves especially the feldspars contain existing weak cleavage planes.

To eliminate the possibility of breakage around the neck area of the tensile specimen, the sharp shoulder or collar was eliminated as described in Model No. 4. The traction was applied to the whole load-bearing area. The stress near the corner of the load-bearing area

was greatly decreased from 8.8-9.3 MPa to 4.68 MPa, which is lower than the theoretical tensile strength of 5.25 MPa, at the center section of the specimen. The theoretical tensile strength is calculated based upon a pull load of 2.66 kN at failure, assuming the failure occurs at the center section of the specimen.

Model 4 provides fairly uniform tensile stresses along the center section. Near the skin of the specimen the stress is approximately 1% lower than the theoretical value. In this case, the tensile strength of the rock specimen can be calculated based on the pull load at failure providing the rock samples are not affected by grinding during the sample preparation process.

11. TENSILE STRENGTH RESULTS

The tensile strength values, σ_t, obtained by the Brazilian test, the triaxial extension test and the direct tensile test, were 5.06±0.72, 1.56±1.08 and 1.47±0.39 MPa respectively at the 420 level. Tensile strength values determined for the samples from the horizontal borehole 213-031-S3 at the 240 level [3], were 6.98±1.05, 3.39±0.29 and 3.53±0.03 MPa for the Brazilian test, the Luong tensile test [4] and the direct tensile test respectively. The tensile values of rock samples obtained from the 420 level were considerably lower than the 240 level. The values at the 420 level were expected to be lower as evidence of higher in situ ground stresses have been observed at this level [6]. The higher in situ horizontal ground stresses at the 420 level, induce greater stress-relief microcracking to the rock core during sampling than at the 240 level. The lower tensile strength values determined for the 420 level suggest the presence of higher in situ ground stresses at this level.

12. OBSERVATIONS

The tests performed using the new direct tensile apparatus yielded tensile strength values comparable with the triaxial extension method, but not with the Brazilian values. The direct tensile test yielded lower strength values than the Brazilian test as the direct tensile test is affected to a greater degree by the presence of microfractures and microfissures in the rock. The rock fails according to the 'weakest link'. For the specimens tested in direct tension and triaxial extension, failure occurred on a plane at or near the mid-section and perpendicular to the axis of the core.

The Brazilian test specimens failed vertically in a line through the points of load application according to theory. The higher value of tensile strength for the Brazilian test series was confirmed with two other rock suites [7]. Pink granite from Cold Spring Quarry,

Pinawa, Manitoba had a Brazilian tensile strength of 9.48±0.53 MPa and a direct tensile strength of 4.87±1.45 MPa. Diabase from Lac St. Jean, P.Q. had a Brazilian tensile strength of 16.33 MPa and a direct tensile strength of 10.39 MPa. For the pink granite, grey granite and diabase, the Brazilian tensile strengths were 40%, 71% and 36% greater respectively, than the direct tensile strengths. In all cases the triaxial extension and the Luong test results compared well with the direct tensile strength results.

13. DISCUSSION AND CONCLUSIONS

The stress analyses based on either NAOS or SAP2D software are for an elastic, isotropic and homogeneous rock type. If the rock samples comply with the assumptions as described, the tensile specimen, such as Model No. 1, 2 and 3, should break at the collar of the specimen where the tensile stress is the highest. Five plexi-glass specimens were prepared according to Model 1 and tested in tension. The plexi-glass specimens were assumed to be homogeneous and isotropic. All of the plexi-glass specimens failed in tension at the neck confirming the stress analyses. At the present, it is not clear that the breakage at the central portion of the grey granite specimens is due to the effect of stress release or due to the inhomogeneity of the rock type, i.e., the presence of large-sized grains in the granite.

The grey granite tensile strength was determined using the new direct tensile apparatus. The tensile strength was found to be 1.47±0.39 MPa. Brazilian tensile strengths were found to be 71% higher. It is suspected that the micro-fissures of the core samples may contribute to the lower tensile strength determined from the direct tensile test.

Tensile strengths determined using the triaxial extension test method compared well with the tensile strength result obtained using the new direct tensile test apparatus. The test program confirms higher tensile strengths are obtained when using the Brazilian test method. The Brazilian test results are not to be discounted, as they may more accurately represent the stresses that come into play in the in-situ case, whereas the direct tensile test results are based on failure at the 'weakest link' in the rock mass.

14. RECOMMENDATIONS

The low tensile strengths obtained indicate that the rock mass at the 420 level and at this borehole location may have micro-cracks, micro-fissures and/or horizontal stresses present. It is therefore recommended that additional tensile tests be conducted on rock core originating from the 420 level at other borehole locations. Large diameter core would allow the Luong tensile test method to be used in such a proposed test program.

To validate the failure mechanism, subsequent tensile specimen geometry has been modified. To eliminate the high stress concentrations around the collar of the tensile specimen and to provide a uniform stress distribution through the center section of the test specimen, the geometry which is similar to Model No. 4 has since been adopted. Further to this, the central uniform section 10 mm in length, has also been incorporated.

15. REFERENCES

1. Vutukuri, V.S., Lama, R.D. and Saluja, S.S. "Handbook on mechanical properties of rocks"; *Trans Tech Publications, U.S.A.*; 1974.

2. Brown, E.T. "Rock characterization testing and monitoring"; *ISRM*; *Pergamon Press, London, England*; 211p; 1981.

3. Wells, J. "Tensile strength tests on URL rock samples from borehole 213-031-S3"; *Report unpublished*; CANMET, Energy, Mines and Resources Canada; 1991.

4. Luong, M.P. "Direct tensile and shear strengths of Fontainebleau sandstone"; *CNRS UA* 317; Solid Mechanics Laboratory, Ecole Polytechnique, Palaiseau, France; 1988.

5. Brace, W.F. "Brittle fracture of rocks";*Memorandum RM*-3583; Int. Conf. on State of Stress in the Earth's Crust-Preprints of Papers; pp2-5 to 2-103; May, 1963.

6. Martin, C.D. "Characterizing in situ stress domains at the AECL underground research laboratory"; *Can. Geotech. J. VOL.* 27; pp631-646; 1990.

7. Gorski, B. "The tensile strength of Cold Spring Quarry granite determined by using four different test procedures"; *Report* $91-040(TR)$; CANMET, Energy, Mines and Resources Canada; 1991.

8. Toews, N.A. and Yu, Y.S. "SAP2D Documentation (vax-11/750 version) - 2D linear elastic finite element program"; *Report* $85-35(TR)$; CANMET, Energy, Mines and Resources Canada; 1985.

9. Yu, Y.S. and Toews, N.A. "A computer program for finite element analysis of axisymmetric solids subject to arbitrary loading (vax/vms version) "; *Report* $86-48(TR)$; CANMET, Energy, Mines and Resources Canada; 1986.

Table 1 Specimen Test Data

Sample Depth (m)	Test Type	Density (Mg/m^3)	σ_t (MPa)
45.950	Brazilian	—	-4.74
40.976	Brazilian	—	-4.95
41.006	Brazilian	—	-4.71
41.256	Brazilian	—	-5.77
41.282	Brazilian	—	-5.73
41.524	Brazilian	—	-5.54
41.548	Brazilian	—	-4.56
41.573	Brazilian	—	-3.98
41.840	Brazilian	—	-4.42
44.242	Brazilian	—	-6.23
mean			-5.06
std. dev.			±0.72
41.044	Direct	2.62	—
41.150	Direct	2.63	-1.81
41.321	Direct	2.62	-1.25
41.421	Direct	2.62	-1.39
41.627	Direct	2.62	-1.16
41.733	Direct	2.62	-0.86
41.031	Direct	2.61	-2.21
44.136	Direct	2.63	-1.34
44.314	Direct	2.62	-1.50
45.800	Direct	2.62	-1.67
mean			-1.47
std. dev.			±0.39
40.843	Extension	2.62	-1.03
44.477	Extension	2.62	-1.41
44.571	Extension	2.63	-0.93
44.800	Extension	2.63	-2.46
44.889	Extension	2.63	-0.91
45.042	Extension	2.62	-1.21
45.134	Extension	2.63	-4.17
45.900	Extension	2.62	-1.47
46.047	Extension	2.62	-1.72
46.234	Extension	2.63	-0.30
mean			-1.56
std. dev.			±1.08

Table 2 A Description of the Numerical Models

Models	Model 1	Model 2	Model 3	Model 4
Geometry	ABCDEFGA	ABCDEFGA	A'B'CDEFGA'	A'B'CC' FGA'
Length L_1 (cm)	5.08	5.08	5.08	5.08
Length L_2 (cm)	0.0	0.0	0.635	0.635
Radius r_1 (cm)	1.2700	1.2700	1.2700	1.2700
Radius r_2 (cm)	1.9050	1.9050	1.9050	1.9050
Radius r_3 (cm)	2.2225	2.2225	2.2225	2.2225
Constraints	$\delta_z = 0$ along AB $\delta_z = 0$ along AG	$\delta_z = 0$ along AB $\delta_z = 0$ along AG	$\delta_z = 0$ along A'B' $\delta_z = 0$ along A'G	$\delta_z = 0$ along A'B' $\delta_z = 0$ along A'G
Area where tractions are applied (cm^2)	4.11699 (ring DE)	3.1471258 (ring D'E)	4.11699 (ring DE)	4.11699 (ring CC')
Tractions applied (MPa)	6.461	8.45215	6.461	6.461
Pull load at failure (Kn)	2.66	2.66	2.66	2.66

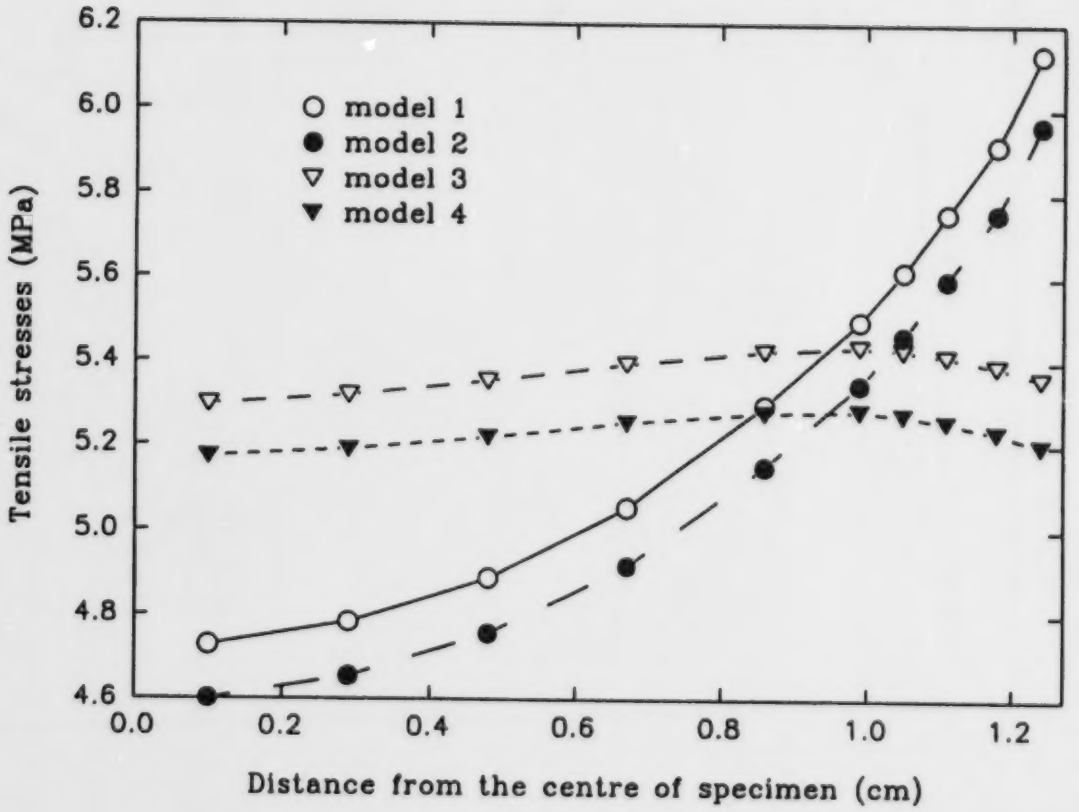


Fig. 7 Stress along the center section of the specimen (section AB or A'B')

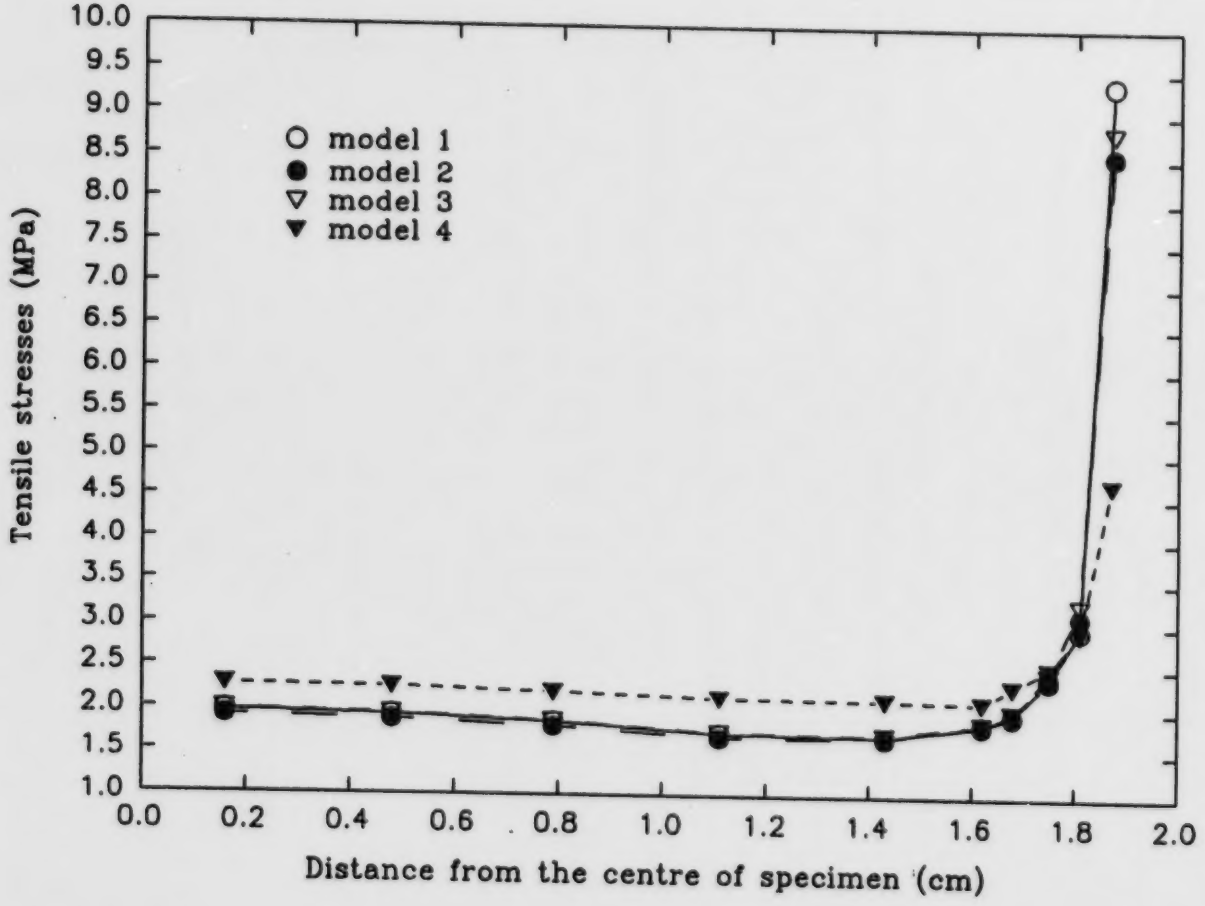


Fig. 8 Stress along the `neck' section of the specimen (section D''D or C''C)